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THE AC 2000: THE ASTROGRAPHIC CATALOGUE ON THE SYSTEM DEFINED BY THE *HIPPARCOS* CATALOGUE

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ABSTRACT

The AC 2000 is a positional catalog of 4,621,836 stars covering the entire sky. The average epoch of position is 1907. The data are from the images measured and published as part of the Astrographic Catalogue (AC). The positions are on the system defined by the *Hipparcos* Catalogue, having originally been reduced plate-by-plate using the Astrographic Catalog Reference Stars. In addition to the astrometric data, magnitudes (on the Tycho *B* system) and cross-referencing information are included. These positions are valuable for the computation of proper motions, and were combined with the positions from the recently released Tycho Catalogue to improve proper motions of almost 1 million stars. The resulting catalog is known as the ACT Reference Catalog (the name ACT is from *AC* 2000 and *T*ycho). Both the AC 2000 and ACT are now available on CD-ROM and can be obtained by contacting the first author above. A World Wide Web site describing various aspects of the reductions is also maintained by the Astrometry Department, US Naval Observatory.

Key words: astrometry—catalogs—reference systems—surveys

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1. INTRODUCTION

Accurately determined proper motions for a large set of stars are of utmost importance to many areas of astronomy, in particular, Galactic studies. Galactic models, including structure and dynamics, are improved with each successive high-quality proper-motion catalog that is released. No doubt the availability of the *Hipparcos* Catalogue (ESA 1997), with position, motion, and parallax precisions near 1 mas, 1 mas yr^{-1}, and 1 mas, respectively, for about 120,000 stars will lead to better modeling. However, some areas of research suffer because larger data sets comprising millions of stars are required. The data required to determine accurate proper motions are needed now. Traditionally, proper motions are determined by comparing catalogs of star positions whose observations are separated by many years. An invaluable source of early epoch positions of 4.6 million stars is the Astrographic Catalogue (AC).

It has been recognized for decades that the data contained in the AC were irreplaceable for the determination or improvement of proper motions (Eichhorn 1974). It has also been recognized that in order to fully utilize the data, new reductions of the plate measures were needed because the *provisional* plate constants (those published in the volumes) failed to maintain the precision inherent in the plate measures and introduced sizable systematic errors. Until recently, however, new reductions could not be made because the data had not been machine-readable, and there was no reference catalog able to adequately reduce the material.

Earlier attempts at new reductions of the AC data met with limited success. Gunther & Kox (1970) derived new plate constants for all plates north of +31° using the Astronomische Gesellschaft Katalog (AGK3) as a reference catalog. Also using the AGK3, Lacroute & Valbousquet (1974) rereduced the data between -2° and +31°. Both works demonstrated that with an adequate reference catalog, improvements in positional standard deviations of individual images could be improved from about 1 $''\!.0$ to $0''\!.3$. However, the AGK3 was unsuitable for AC reductions because of its lack of stars in the Southern Hemisphere and its systematic deviations from the standard reference system (the FK4, at the time). Herget (1973) demonstrated the feasibility of combining many individual catalogs into one reference catalog that would be free of distortions found in the AGK3. One of the authors (T. E. C.), who worked closely with Herget, was impressed with the results and decided that a global reference catalog formed by the combination of transit-circle and photographic data was the best way to rereduce the AC data. In 1991, this catalog was released as the Astrographic Catalog Reference Stars (ACRS; Corbin & Urban 1988, 1990). New reductions of the entire AC data could now proceed.

This paper outlines the methods used in the US Naval Observatory's rereduction of the Astrographic Catalogue data and the resulting catalog, named AC 2000. The input data, investigation of various plate models, treatment of discordant data, conversion of data to the system of *Hipparcos*, and final catalog characteristics are discussed. The authors acknowledge that this is not the final edition of this catalog. It is probable that a "definitive" version, using refinements in the reference catalogs, new reduction methods, and remeasurements of the data, will supersede this one. However, the AC 2000 described here is the first complete reduction of the Astrographic Catalogue data ever to be made. It is an immense improvement over the previously inadequate or incomplete attempts at this work and is as close to a "definitive" version as can be achieved at this time.

2. HISTORY OF THE ASTROGRAPHIC CATALOGUE

The Carte du Ciel was an international effort begun more than a century ago to determine positions for all stars brighter than 11th magnitude to better than $0''\!.5$ using photographic plates and, using another set of plates, to publish charts representing the relative positions of all stars down to magnitude 14.0. The chart plates proved to be very expensive to photograph and reproduce, so many institutions did not complete this part of the work. However, the astrographic program designed to measure all stars to 11th magnitude was completed. Actually, the original goal of 11th magnitude was generally surpassed. Image positions were usually published in linear units (such as millimeters) with the plate center as the origin. These (x, y)-values with coefficients (e.g., plate constants) and the formulae needed to convert them to equatorial coordinates are known as the Astrographic Catalogue.

In total, 20 observatories from around the world participated in exposing and measuring the plates. Each was assigned a specific zone, between two parallels of declination, to photograph. In order to compensate for any plate defects, each area of the sky was to be photographed twice, using a twofold, corner-to-center overlap pattern. The participating observatories agreed to standardize the type of telescope, so each plate photographed had a similar scale of approximately $60''$ mm^{-1}. The measurable areas of the plates were $130' \times 130'$, and thus more than 22,000 plates were needed (22,660 were exposed and measured since some areas were rephotographed). Information on the data, by observatory, can be found in Table 1. The observatories also agreed to expose a grid, called a *reseau*, on each plate, which was originally used to monitor emulsion shifts. After the shifts were demonstrated to be quite small, the practice of exposing a reseau on each plate was continued because it aided in the measuring of the star positions by letting the measurer refer each image position to the lines of the reseau. In addition, since each reseau unit was approximately 5 mm, the screws used to measure star positions only needed to be accurate over this length. The reseau orientation defined the plate's (x, y) coordinate system. Although telescope type, plate size, and use of a reseau were standardized, many other factors, such as reference catalog used, reduction technique, magnitude measurements, and printing formats were left up to the individual institutions. Additional details regarding the project can be found in Eichhorn (1974) and on the CD-ROM containing the AC 2000.

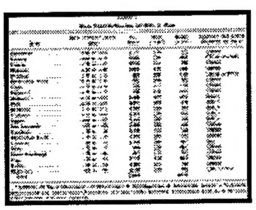


TABLE 1 DATA CONSTITUTING THE AC 2000, BY ZONE

3. INPUT DATA FOR THE AC 2000

Most observatories published their results in several volumes, each volume consisting of measures from plates centered on the same degree of declination. The US Naval Observatory (USNO) library has a complete set of the AC volumes, and the data making up the AC 2000 were taken from those books. Generally, each line in the printed volumes consists of data from one star, including its measured (x, y)-value, a measure of brightness (magnitude or diameter), the plate number, and a running number on the plate. Other data concerning epoch of exposure, hour angle at midexposure, air temperature, barometric pressure, reseau used, observer, measurer, and measuring machine are usually provided in separate tables. In addition, provisional plate constants used to transform the (x, y)-measures to standard coordinates are supplied. The published (x, y)-values have been transferred to a machine-readable form via double-keyboarding (typing each record twice to remove most transcribing mistakes). Institutions participating in this data entry are listed in Table 1. In total, over 8.6 million image measures were double-keyboarded.

Occasionally, lists of printing errors have been published in different sources. Some of these lists are found throughout the volumes themselves (such as the Catania data), and others have been distributed decades after the original volumes' publication dates. To find these lists of errata, all

explanatory introductions to the data, as well as notes throughout the volumes, were read. The Transactions of the International Astronomical Union were consulted, as well as an electronic search on the World Wide Web. When corrections were found, they were applied to the data.

4. PREPARING THE DATA FOR THE REDUCTION SOFTWARE

The reference catalog used throughout the individual plate reductions of the Astrographic Catalogue was the Astrographic Catalog Reference Stars. The ACRS is a dense set of reference stars, about eight per square degree, on the system of FK5, and designed specifically for reduction of the Astrographic Catalogue data. A typical ACRS star at the epoch of an AC plate will have a positional standard deviation of about 200–250 mas per coordinate. The first step in making the new reductions was to match the ACRS stars with the star images on each plate. To do this, equatorial coordinates for all AC images were computed from the rectangular coordinates [the (x, y)'s] via the provisional plate constants published in the volumes. The ACRS data were then brought to the average epoch of each zone and transformed to the AC equinox, B1900.0. A positional match was then made between the AC and ACRS. All plates were checked to ensure that each contained an adequate number of identified reference stars. Fewer than expected matched reference stars on a plate often indicated problems with the published constants or plate centers. These plates were investigated, and the problems were corrected.

The same equatorial coordinates computed in the previous step were used to identify images of the same stars that lie on overlapping plates. Identification of images in common at an early stage of the reductions was critical in handling some types of systematic errors. The data were combined into one standard-format file that contained all pertinent information about each plate and image. A conversion from the published (x, y)-units to units of millimeters, along with a translation of the coordinates so the origin is in the approximate plate center, was performed when necessary.

5. PRELIMINARY REDUCTIONS AND INVESTIGATION OF PLATE MODELS

The AC 2000 was produced by reducing each plate individually and combining images of each star to form weighted mean positions. It is known that an "overlap" solution may be possible (Eichhorn 1960; de Vegt & Ebner 1974), but the Astrographic Catalogue data are poorly suited for such a reduction at this time. Three characteristics make an overlap solution difficult: (1) span of the plate epochs, (2) the overlap pattern, and (3) reference star quality. Most overlap solutions have been made on large plates exposed at nearly the same epoch and with at least a fourfold overlap (Zacharias 1992). Work utilizing the Second Cape Photographic Catalogue (CPC2) data demonstrated that applying an overlap solution can actually degrade positional accuracies if the plates are insufficiently modeled (Zacharias 1993, 1995). The ACRS in its current state is inadequate to do the detailed modeling required by an overlap solution. None of these characteristics necessarily make an overlap solution impossible; this technique will be further investigated in a subsequent version of the AC 2000.

Much of the plate reduction software and methodology was the same as that used in the reductions of the CPC2 data (Zacharias et al. 1992). The conversion of the measured coordinates, (x, y), to

standard coordinates, (ξ, η), is performed by a mathematical model whose coefficients are known as plate constants. For all but the Potsdam, Perth, and Sydney zones, an eight-constant plate model consisting of four orthogonal plate constants (*a*, *b*, *c*, and *d*), two nonorthogonal, linear plate constants (*e* and *f*), and two tilt constants (*p* and *q*) was initially used, as shown in equations (1) and (2):

$$\xi = ax + by + c + ex + fy + px^2 + qxy \, , \qquad (1)$$

$$\eta = ay - bx + d - ey + fx + pxy + qy^2 \, . \qquad (2)$$

For the Potsdam, Perth, and Sydney data, the same plate model was used except the corrections corresponding to the average two tilt terms (*p* and *q*) were preapplied to the data and were not solved on individual plates. Equations (1) and (2), without the tilt terms, are a reorganized version of a standard six-constant plate model. This is done so each coefficient has a physical meaning. Variable *a* is the scale, *b* is the plate rotation, *c* is the offset in the *x*-direction, *d* is the offset in the *y*-direction, *e* is the scale difference in *x* and *y*, and *f* is the axis tilt between *x* and *y*.

At this step, no corrections to the published (*x*, *y*)-values were applied. Since an uncompensated systematic error may cause a star to be an outlier, only reference stars with residuals over 5 times the standard deviation of unit weight of the solution were removed while various plate models were investigated.

5.1. *Corrections to the (x, y)-Values*

Results of investigations of systematic errors may lead to applying corrections to the published star measures prior to final plate-constant determinations. Investigations of radial distortions, tangential distortions, magnitude equation, coma, periodic measuring errors, and nonradial field distortion errors were investigated following procedures outlined previously (Urban & Corbin 1996; Urban et al. 1996). As outlined in those papers, both the residuals of the reference stars and information from overlapping plates were used to determine certain systematic errors. In particular, how coma behaved outside the magnitude range of the reference stars could only be determined by using stars present on overlapping plates. Dependence of these terms on magnitude, measurer, measuring machine, plate epoch, and reseau were analyzed and applied, when appropriate. Using the information from these investigations, a plate model was developed for each of the AC zones. Equations (3) and (4) show the corrected (*x*, *y*)-values, now called (x', y'), used in the final plate adjustments:

$$x' = x + \mathrm{RD} + \mathrm{ME}_x + \mathrm{MC}_x + S_x + \mathrm{MA}_x + \mathrm{FDP}_x\,, \quad (3)$$

$$y' = y + \mathrm{RD} + \mathrm{ME}_y + \mathrm{MC}_y + S_y + \mathrm{MA}_y + \mathrm{FDP}_y\,. \quad (4)$$

In equations (3) and (4), RD is the correction applied to compensate for radial distortion; ME and MC are corrections to compensate for magnitude equation and (x, y)-dependent magnitude equation, respectively; S is the correction for a magnitude-dependent, linear change of scale (hereafter referred to as "coma"); MA corrects for measuring apparatus errors; and FDP compensates for any remaining field distortion pattern. By substituting (x', y') for (x, y) in equations (1) and (2), the eight constants for each plate were computed. The significant systematic errors found and corrected in each zone are listed in Table 2.

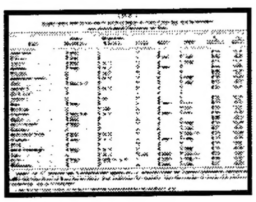


TABLE 2 Corrections Applied to the (x, y) Data Prior to Final Least-Squares Adjustment and Single-Image Precisions, by Zone

6. INVESTIGATION OF DISCORDANT DATA

Once a suitable plate model was determined, the computed positions were used to investigate problems such as mismatched images, blended images of multiple stars, and typographical errors.

6.1. *Rematching Images*

Positions computed from the provisional plate constants can change significantly as a result of the new reductions, and therefore it was necessary to ensure that images were correctly matched. Images closer together than about 3"5 with no sign of duplicity were generally identified as the same star. (Duplicity is indicated if two images are on one plate or there is an entry in the Washington Double Star Catalog [WDS; Worley & Douglass 1996]). The Preliminary Version of the Third Catalogue of Nearby Stars (Gliese & Jahreiss 1991) and the Luyten Two-Tenths Catalogue and its supplement (Luyten 1979–1980; Luyten & Hughes 1980) aided in detecting high proper motion stars, whose positions may not be coincident because of differing plate epochs. Images from different stars incorrectly identified as coming from the same star will result in a high standard deviation in their mean right ascension or declination, $\sigma\alpha$ or $\sigma\delta$, computed using standard formulae. Stars with the largest standard deviations were investigated for incorrectly matched images.

Virtually every zone has mistakenly printed some of its measures more than once. These were easily found since the data in question were either exactly the same as another record (in cases of true duplication) or the resulting star positions of two records were too close for the telescope scale and

typical seeing. In general, images closer than 1″0 that appear on the same plate were suspected of being duplicate entries. In cases of this type, either notes in the published volumes were consulted or a comparison with measures on an overlapping plate was made. Generally, only one of the measures was kept.

6.2. *Blended Images*

Images of double stars that are blended on one plate but discrete on another require special treatment. Two possible problems exist under these circumstances. First, if the blend is identified as one of the separate images, then the computed separation of the double star will be smaller than it is in actuality (since the blend will fall near the photocenter). Second, if the blend is not identified with either discrete image, then three sets of coordinates will be computed where only two stars exist.

Under the first scenario (a blend is matched with a discrete image), the data will consist of a multiple star system with at least one star having a large standard deviation of position, ($\sigma\alpha$, $\sigma\delta$). To investigate this possibility, the area around every star was searched for the presence of another star. If a nearby star was found and one has a high standard deviation of position (usually higher than 0″9), then that system was graphically examined for a blend. In addition, any two stars closer than about 3 ″0, or any triple or quadruple systems, were examined.

Under the second scenario (a blend is not identified with either of the discrete images), then a star system will appear to have one more member than it really has. To minimize this occurrence, an area with radius of about 10″ around each star was searched for the presence of two other stars. In addition, an area with a radius of about 15″0 was searched for three other stars. If multiples were found, they were examined to ensure that the images were identified correctly. In the situations described above, blends are discarded.

6.3. *Typographical Errors*

A bright star may only appear to have one image if one of its records contains a typographical error (many faint stars are only on one plate because of the varying magnitude limits of the plates). To find and correct typographical errors in the published (x, y)'s, all bright single-image stars were investigated. The exact magnitude limit depended on the zone. Typically, all stars down to 11.5 were investigated. The process involved generating positions for these images if one of the digits of the printed x- or y-value was altered and then performing a search around these pseudopositions. If another image was found at one of the locations, a typographical error might be present. The Twin Astrograph Catalog (TAC; Zacharias et al. 1996) was used to determine which of the two, if either, should be changed for all zones north of, and including, Tacubaya. For the more southerly zones that are not covered by the TAC, the Tycho Input Catalogue (Halbwachs et al. 1994) was used. If a corresponding star was not found in either of these catalogs, then a search of the Digitized Sky Survey (Lasker et al. 1996) using the SkyView interface (McGlynn, White, & Scollick 1994) was made to determine which, if either, contains a typographical error.

To minimize the possibility of a printing error in the magnitude data, a standard deviation of the

magnitude, σ_{mag}, was generated from the computed magnitudes for every star appearing on more than one plate. The stars with the largest σ_{mag} were investigated. In addition, range checks were made on the original data, as well as the final computed magnitudes, to ensure that all values were reasonable.

6.4. *Nonstellar Objects*

To avoid the presence of nonstellar objects in the final catalog, a search in the New General Catalogue of Nebulae and Clusters of Stars (NGC), the Index Catalogue (IC), and the Second Index Catalogue (Sinnott 1988) was made. The Digitized Sky Survey, using the SkyView interface, was used to graphically show potential NGC and IC objects present in the data. Those records found to be nonstellar NGC or IC objects were discarded.

7. FINAL PLATE MODEL, WEIGHTS, AND ZONE LINKING

It was necessary to ensure that the plate model was still valid, because it was originally developed on the data that included erroneous identifications and typographical errors. Once any needed revisions were made, weights were assigned. Weights were used because measuring precision varied from plate to plate, and measurements from poorly exposed and measured plates naturally should be given less influence than well-exposed, well-measured images of the same star. Often an image's weight is computed as a function of plate-constant variance, x, y, and magnitude (Eichhorn & Williams 1963). However, with generally two images per star, it is possible that one image will completely dominate the final position. Since it was shown that a strong correlation between plate measurer and measuring precision exists (Urban et al. 1996), one weight is assigned to all images on each plate. For most of the AC zones, a plate's weight is proportional to the reciprocal of the variance of the positions of the stars that it contains (from comparisons with overlapping plates), after removing the stars with the highest 1% $\sigma\alpha$ and $\sigma\delta$. The removal of these stars prior to computing the plate weights reduced the possibility that a few high proper motion stars adversely affected the weighting of an entire plate, since some zones contain overlapping plates with large epoch differences. Plate weights not only took into account the scatter in the differences with the mean positions, but they were also lowered if an entire plate appeared offset from the overlapping ones.

No diffraction grating was used in the AC program, so bright stars are overexposed on the plates and should neither be used in the final adjustment nor be included in the final catalog. All stars with mean computed magnitudes brighter than 4.0 were removed prior to final plate adjustments. Reference stars with residuals larger than 3 times the standard deviation of unit weight of the plate solution were removed from the final plate-constant solution, and the plate adjustment was performed again. These stars were included in the final catalog but were not used in the computation of plate constants.

The Astrographic Catalogue was observed in discrete zones in the sky, and the reductions, by necessity, were made on individual zones. However, it is desirable to link these together to make one cohesive catalog following the individual plate reductions. To do this, stars in common to adjacent zones were identified. Blended images, high proper motion stars, and typographical errors were

investigated as described above. All images of each star were combined to yield weighted mean right ascensions and declinations in the FK5 system at the weighted mean epochs of observation for the equinox J2000.0. This intermediate version of the reductions is not being distributed, but will be referred to in this paper as AC/FK5.

8. CONVERSION OF THE AC MAGNITUDES

The Astrographic Catalogue contains nonuniform magnitude measures, in part because of different techniques used by participating observatories. Many of the published magnitudes are unreliable, especially for the faintest and brightest stars. Thus, it is desirable to transform the magnitudes to some well-known (or often used) system. The plates used were most sensitive in the blue spectral region. Therefore a logical choice of systems was Tycho *B*, since the Tycho Catalogue (ESA 1997) contains about 1 million stars covering much of the AC magnitude range.

Each zone was treated independently. Only stars identified in the Tycho Catalogue as being single and with negligible variability were used for the calibration. Differences between AC and Tycho *B* magnitudes as a function of AC magnitude were computed. Polynomial expressions describing the results were computed using least-squares fitting. Some extrapolation of these polynomials was required because, in general, the Tycho Catalogue is not as faint as the AC. (Usually an extrapolation of less than 0.5 mag was used. Beyond that, the corrections were held constant.) Figure 1 shows one such plot for the Hyderabad North zone. Corrections based on functions such as that seen in Figure 1 were applied to each observation within the zone. In reality, these magnitude offsets can differ from plate to plate and are functions of plate coordinates (Turner 1912, p. 51). However, since the published measures are often inaccurate and of low precision by photometric standards, it was necessary to look at groups of plates and take care of the major systematic differences. It must be stressed that the intent of the original AC was not to produce photometric results; thus, the magnitudes in the AC 2000 should be used primarily for identification purposes and not for photometric studies. However, in a broad sense, the magnitudes contained in the AC 2000 are close to those of the Tycho *B* data, as shown in Figure 2.

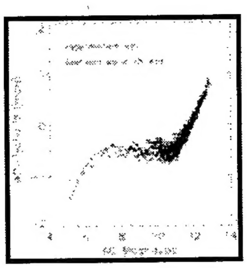


FIG. 1.—Differences in magnitude between the Hyderabad North zone and Tycho *B* data as a function of published AC magnitude. Each point is the average of 100 stars. For clarity, error bars are not included, but are typically about ±0.05 mag in size.

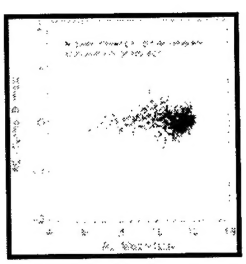


FIG. 2.—Differences in magnitude between the AC data and Tycho *B* data following conversion to the Tycho system. Each point is the average of 100 stars. For clarity, only every 25th point is plotted.

9. CONVERSION TO THE *HIPPARCOS* SYSTEM

The conversion of the FK5-based Astrographic Catalogue (AC/FK5) to the system defined by *Hipparcos* was necessary because the *Hipparcos* Catalogue (ESA 1997) is now recognized as the standard reference frame at optical wavelengths, following the passage of resolution B2 at the Kyoto IAU General Assembly (IAU 1998). Prior to this conversion, systematic errors between AC/FK5 and *Hipparcos* positions are frequently 200 mas or greater, primarily because of the differences between the FK5-based ACRS and *Hipparcos* at the epochs of the AC plates. This is seen in Figure 3, which shows the differences between AC/FK5 and *Hipparcos*, as well as between the ACRS and *Hipparcos*. Both figures have been computed near the average AC epoch.

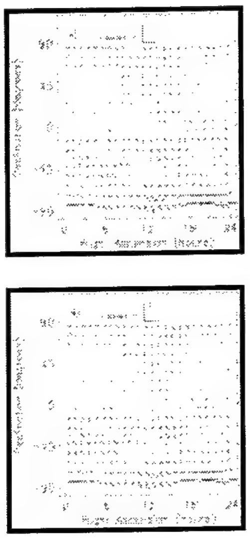


FIG. 3.—(*a*) Systematic differences between the AC/FK5 and *Hipparcos*. (*b*) Differences between ACRS at epoch 1900.0 and *Hipparcos*. The data have been lightly smoothed (that is, some effect from adjacent bins is present) to minimize random noise. The similarity of the two plots demonstrates that the AC/FK5 is indeed on the system defined by the ACRS, but a further reduction to the *Hipparcos* system is required.

The conversion from AC/FK5 to the *Hipparcos* system was made in three steps. First, stars in common between the AC/FK5 and *Hipparcos* were identified. Systematic differences between the two catalogs were found and applied according to the following method: For each AC position, all AC observations of *Hipparcos* stars within a 2° radius were identified. Differences between the AC observations and the *Hipparcos* positions at the AC epoch were computed for those stars. Each observation of a *Hipparcos* star was weighted using a parabolic function; those closest to the central AC star were given the most weight while those near 2° away given the least. The weighted mean residual was computed and applied to the central AC observation. At this stage, no individual residuals exceeding 1500 mas were included in the computation of the mean.

Second, it is possible that a magnitude equation, a systematic change in position as a function of magnitude, remains in the AC positions as a result of the presence of one in the ACRS or a remaining one in the original AC measures. Thus, each of the 22 zones needed to be analyzed and corrected independently. In each case, mean residuals (AC minus *Hipparcos*) as a function of magnitude were computed and described by a least-squares fit to a polynomial function. Each observation was then corrected based on the value of the polynomial function. To demonstrate this, the residuals in right ascension of the Toulouse zone before and after this correction are shown in Figure 4.

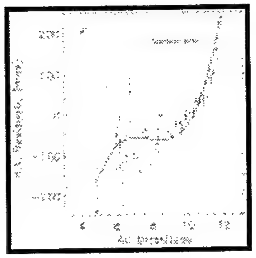
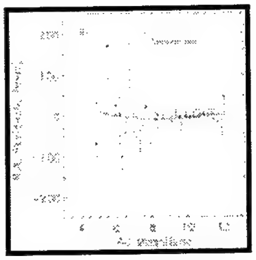


FIG. 4.—Differences in right ascension between the Toulouse zone and *Hipparcos* data as a function of magnitude, both (*a*) prior to the application of corrections and (*b*) following the corrections. Curves represent a third-order least-squares fit to the data points. Each point is the average of all stars in a 0.2 magnitude range.



The third step is a repetition of step 1, which was necessary for convergence. During this step, no residuals exceeding 750 mas were used. The systematic differences between the newly reduced AC and *Hipparcos* data at the AC epochs are shown in Figure 5. The lack of any noticeable patterns such as those seen in Figure 3 demonstrates that the conversion to the *Hipparcos* system was successful. Similar plots using only those stars within a specific magnitude range (to investigate remaining magnitude equation) were made and also show no pattern. Individual observations of each star were combined, and mean positions were computed. The resulting catalog is called AC 2000.

FIG. 5.—Systematic differences between the AC 2000 and *Hipparcos*, at the AC epoch. The data have not been smoothed. Each point is an average residual within a $1^h \times 10°$ area. Near the poles few stars are contained within each area, and the random errors dominate. The standard deviation of each "point" spans from 11 mas per coordinate in the equatorial regions to 35 mas per coordinate at the poles. The lack of any noticeable pattern such as those seen in Fig. 3 demonstrates that the conversion to the *Hipparcos* system was successful. Note the scale difference between Fig. 3 and this plot.

10. INVESTIGATIONS OF OTHER SYSTEMATIC ERRORS

Figure 6 shows positional differences between the AC 2000 and *Hipparcos* (at the AC epoch) with respect to the AC 2000 magnitude. Little difference between the two catalogs based on magnitude is seen. Positional differences plotted with respect to the *Hipparcos* $B - V$ color index are shown in Figure 7. No systematics in right ascension are noticeable. However, there is a *color term* in declination present in the data. Globally it totals about 30 mas mag^{-1}. However, this is more pronounced for the northern zones than the southern, reaching about 50 mas mag^{-1} in some areas. Whether this effect is a result of the telescope optics, the ACRS, or another source is still under investigation. Over 20 years ago, Eichhorn (1974) mentioned the difficulty in handling color-dependent terms in the AC data, and unfortunately his words are still true. Since fewer than 25% of the AC 2000 stars have reliable color indexes, no corrections can be made at this time.

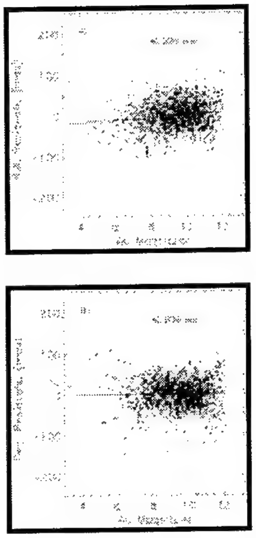


FIG. 6.—Positional differences between AC 2000 and *Hipparcos* by magnitude. For clarity, error bars are omitted, but are typically ±30 mas in size. Each point is the average of 200 observations.

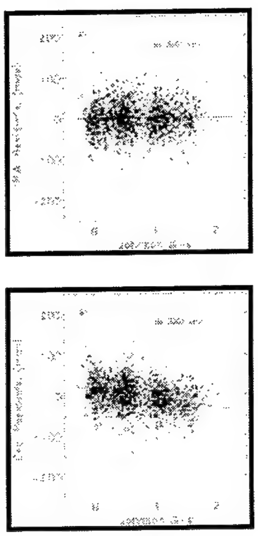


FIG. 7.—Same as Fig. 6, but by color index

11. CATALOG CHARACTERISTICS

The AC 2000 contains positions, magnitudes, error estimates, and cross-references for 4,621,836 stars. The positions are on the system defined by *Hipparcos*, at the epoch of observation. The magnitudes are close to those of the Tycho *B* data. Error estimates are based on positional coincidence of images from overlapping plates. Cross-references to *Hipparcos*, Tycho, and the ACRS catalogs are also provided. Figure 8 shows the density of stars in the AC 2000, and Figure 9 shows the mean epochs. The banded structure seen in Figure 9 is the result of different observing dates for the participating observatories. Figure 10 shows the average standard deviations with respect to position on the sky. Three bands of low precision are evident. These correspond to the Vatican, Potsdam (later photographed by Uccle, Hyderabad, and Oxford), and Sydney zones. The equatorial region showing the highest precision corresponds to "French zones," all measured with the labor-intensive *short screw* micrometers. Figure 11 shows the number of stars per magnitude.

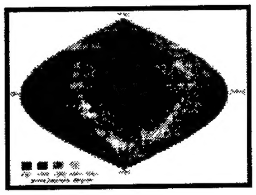


FIG. 8.—Stellar density of AC 2000

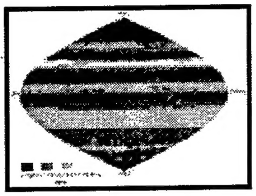


FIG. 9.—Mean epochs of AC 2000

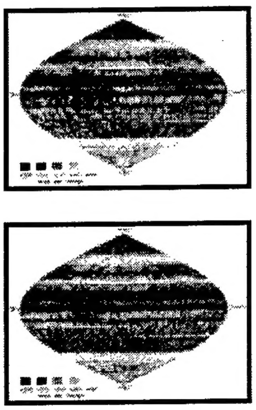


FIG. 10.—Positional standard deviations $\sigma\alpha$ (*top*) and $\sigma\delta$ (*bottom*) of AC 2000

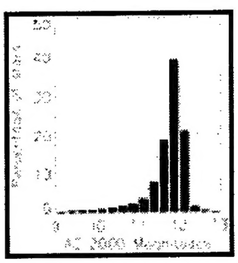


FIG. 11.—Magnitude distribution of AC 2000

12. DISCUSSION

Because of the early epochs and reasonable accuracies of the AC 2000 positions, the catalog is invaluable for determining or improving proper motions. One of the first uses of the AC 2000 has been to recompute proper motions contained in the Tycho Catalogue; the resulting data have been distributed as the ACT Reference Catalog (Urban, Corbin, & Wycoff 1998). As a demonstration of the improvement, consider the following example: A standard deviation in a coordinate, σ_z, some Δt years after a star is observed at position z_0, is

$$\sigma_z = \sqrt{(\Delta t \sigma_\mu)^2 + \sigma_{z0}^2}\,, \tag{5}$$

where $\sigma\mu$ is the standard deviation of proper motion of coordinate z and σz_0 is the error of z_0. Note that equation (5) is true if σz_0 and proper motion, μ, are derived independently. Using the Tycho data alone, with positional error (σz_0) of 25 mas at epoch 1991.25 and proper-motion error of 25 mas yr^{-1}, the error in position at epoch 2000.0 is 220 mas. Using a combination of AC 2000 and Tycho positions, a typical proper-motion error based on both catalogs' stated precisions is roughly 3 mas yr^{-1}. The positional error of a Tycho star using this new proper motion is 36 mas at epoch 2000.0. The differences become even more pronounced at epochs further from that of Tycho. In combining the AC 2000 with modern data, high-accuracy reference catalogs, good for applications spanning many decades (such as reducing large Schmidt camera surveys such as POSS-I and POSS-II), can be developed.

In time, improvements will be made to the AC 2000. As shown above, color-dependent systematic terms remain. When accurate photometry becomes available for the majority of the stars, many of these effects can be removed. In addition, systematic errors such as magnitude equation may be present for the fainter stars. Since the ACRS and *Hipparcos* catalogs have few stars fainter than magnitude 11.0, accurate investigations and removal of systematic deviations for faint stars were impossible. A recompilation of the ACRS can improve a later version of the AC 2000 since all ACRS input data can now be reduced directly to the *Hipparcos* system, and new catalogs not available in the 1980s can be included. This will lead to a reference catalog having an increase in precision as well as accuracy and an extended magnitude range. Changes in the plate reduction method can be modified, thus leading to an improved catalog. For example, one can subjugate certain plate parameters to stochastic restriction (Eichhorn 1978). Another improvement may be made by utilizing an overlap solution, but further investigations regarding the improved accuracies should be carried out.

The largest improvement, in terms of accuracy and additional stars, will undoubtedly occur with a remeasurement of the plates. A working group sponsored by Commissions 8 and 24 of the IAU was formed to investigate the possibility of remeasuring the existing AC and "chart" plates. Pilot projects are underway at several institutions (IAU 1998). Some of the "chart plates," with limiting magnitude near 14.5, have been measured, and positional precisions on the order of 100–200 mas appear achievable (Geffert et al. 1996). Remeasurement (or initial measurement in the case of the "chart" plates) is a major undertaking and will not be completed for several years.

13. SUMMARY

The image measures published as part of the Astrographic Catalogue have, for the first time, been reduced to a common, global reference system and combined to form a single all-sky catalog. This catalog, called AC 2000, contains positions on the *Hipparcos* system and magnitudes close to Tycho *B* for 4,621,836 stars. The AC 2000 is now being distributed by the US Naval Observatory via CD-

ROM and the World Wide Web.[3] Those interested in obtaining the data can contact S. E. U. via electronic mail.

[3] At http://aries.usno.navy.mil/ad/ac.html.

We wish to acknowledge those who have contributed time and effort to ensure that the AC 2000 is of the highest quality. Thanks are extended to Christopher Sande, James Muse, J. Craig Doty, and Harry Crull, all of whom helped verify error rates in the keyboarded data. Thanks are given to Varkey Kallarakal, Steve Boretos, and Brenda Hicks, who spent many hours keyboarding plate information needed in the reduction process. Norbert Zacharias's insight was invaluable for investigating and minimizing systematic errors. Finally, a special gratitude is extended to the hundreds of men and women, most of whom have long since passed away, who exposed and measured the 22,660 AC plates.

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